June 21, 2024
Evaluating Snow Depth Retrievals from Sentinel-1 Volume Scattering over NASA SnowEx Sites
By: Z. Hoppinen et al.

Reviewer comments are shown in black. Responses are in blue.

Response to Reviewer #1

General Comments:

A novel method to retrieve snow depth from C-band Sentinel-1 observations was previously introduced by Lievens et al. (2019). While potentially very valuable as a novel source of snow information, the study has also caused a degree of debate in the community due to the conventionally assumed insensitivity of radar backscatter at this frequency to snow accumulation. Although new theoretical analysis suggests that such sensitivity may be possible in certain cases indirectly through the sensitivity of cross-polarized backscatter to anisotropic snow structures, an independent validation of the method beyond some case studies has been largely lacking. The study by Hoppinen et al. attemps just this, providing a potentially valuable contribution to the community, also by giving access to an open-source software replicating the snow depth retrieval method.

The study itself is well written and clear. I find the presentation of results convincing and thorough. I recommend publication of the paper, after considering the following few minor suggestions.

We thank the reviewer for these insightful comments. Accordingly, we have modified the manuscript with the changes highlighted below and believe that the manuscript is much improved with these corrections.

Minor comments

1. Abstract line 8: 2020-2021

   Changed from 2020-21 to 2020-2021

2. Abstract line 9 and throughout the paper; “poor agreement”. While I agree with the authors that the agreement is indeed poor, I would still suggest another way of pointing this out. Also, I’m not sure anyone has quantified what is “poor”… e.g. just stating the R value and nRMSE should be sufficient for readers to make their own conclusions. You can always cite requirements placed on e.g. nRMSE, as you have done in several places.

Also you could cite values obtained with PMW (e.g. Mortimer et al., 2022). In the abstract you could just say the achieved accuracy "is considerably lower than requirements placed for remotely sensed observations of SD" or something similar.

We appreciate this suggestion and agree that "poor" is somewhat vague. We have modified this section of the abstract to read "Across all sites, we find agreement between the Sentinel-1 snow depth retrievals and the lidar snow depth measurements to be considerably lower than requirements placed for remotely sensed observation of snow depth, with a mean RMSE of 0.92 m and a mean Pearson correlation coefficient R of 0.46."

3. Introduction, line 36 "passive microwave measurements saturate" only applies to the 37 GHz frequency typically used in retrievals. Please reword.

   Added "at the typically used 37 GHz" (line 37)

4. Introduction, around line 60. Here, it would be appropriate to briefly acknowledge the diverse methods SAR could be used to retrieve SD/SWE: 1) repeat-pass InSAR at low frequencies to obtain deltaSWE 2) single-pass InSAR (DEM differencing) to obtain SD 3) volume scattering approach to obtain SWE directly. Please add also a few appropriate references. You can then tie Lievens et al. more or less to the volume scattering approach, giving a motivation for section 1.1. Please also recap some of the difficulties associated with the volume scattering approach, namely the separation of ground and snow backscattering contributions, as well as the influence of snow microstructure.

To address this reviewers concerns, we have added the following new paragraph to the introduction of the manuscript (line 62-71):

"Numerous techniques have been explored to extract snow depth or SWE from SAR imagery. Such techniques include evaluating backscatter changes to retrieve snow characteristics (Ulaby and Stiles, 1980; Bernier et al., 1999; Shi and Dozier, 2000; Chang et al., 2014; Lievens et al., 2019), using change in travel time information between image acquisitions to approximate SWE changes (Guneriussen et al., 2001; Deeb et al., 2011; Li et al., 2017b; Dagurov et al., 2020; Marshall et al., 2021; Ruiz et al., 2022; Tarricone et al., 2023; Palomaki and Sproles, 2023; Oveisgharan et al., 2023; Hoppinen et al., 2024), exploiting SAR travel time change sensitivity to local slope to capture SWE (Eppler et al., 2022), differencing DEMs for snow depth (Leinss et al., 2018), using differences in the polarimetric response of radar travel times (Leinss et al., 2014, 2016; Voglimacci-Stephanopoli et al., 2021), using travel time changes of frequency subswaths for SWE estimates (Engen et al., 2004), and utilizing phase noise in SAR imagery for snow coverage (Shi et al., 1997; Singh et al., 2008). More detailed discussions of these techniques are available in Tsai et al. (2019), Awasthi and Varade (2021), and Tsang et al. (2022)."

5. Section 1.1, line 75. Surface scattering contributions for dry snow should be very small compared to volume scatter and ground backscatter. This could be good to point out, perhaps with a reference?

This is true, however surface scattering is also wavelength and incidence angle dependent. Multiple studies of avalanche debris have suggested that surface-roughness factors likely contribute a substantial amount of backscattered energy at C-band. We found this point interesting and have decided instead to highlight the implicit assumption that this surface scattering is relatively unchanged throughout the winter or is correlated with snow depth and hence folded into the algorithm (line 99; Figure 1).

6. section 1.1 line 77 "Some SAR-based methods…" brings up the question of what other methods there are. See previous comment #4, please reword.

Reworded this section to "Higher frequency SAR systems". See the major revisions we have made for this in response to your comment #4.

7. section 1.2, lines 111 and 115, maybe elsewhere: suggest to change "in Lievens et al." to "by Lievens et al."

Changed from "in Lievens" to "by Lievens" as suggested and two other locations.

8. Section 2.2 lines 163-164. Sentence seems out of place/complementary of what comes on lines 165-166. Remove?

Removed.

9. section 2.2 line 174 & elsewhere. I guess the parameters A, B and C are not actually dimensionless? delta SD should come out as meters?

A and B are dimensionless and C has units of m/dB. We have added the following sentence in Section 2.2 to clarify the parameter units: "Note that A and B parameters are dimensionless while C has units of m dB^{-1}." (line 193-194)

10. Section 2.2 line 187. I find the rather limited correlation surprising, it is a pity that apparently this could not be pursued further. I'm also a bit lost why the intercomparison between the products produces a R value of 0.64, when comparisons to lidar data are apparently very similar between the two… can you elaborate still on the comparisons to lidar data? Did this represent e.g. a subset of the product intercomparison? Maybe even

some map comparisons between C-SNOW and your retrievals could be in order e.g. in the Appendix?

There exist multiple challenges with comparing our retrievals to the C-SNOW product.

The main challenge with comparing the two snow depth datasets is that the published methods in Lievens et al. (2022), which we follow here as closely as possible from their description in the paper, differ from the actual methods used to generate the data and figures in the paper as well as the data available in the C-SNOW repository (https://ees.kuleuven.be/eng/apps/project-c-snow-data/). This discrepancy was confirmed to us by personal communication with Dr. Hans Lievens which we cite in our manuscript (line 216). Additionally there is little to no documentation or metadata available on C-SNOW to clarify which data version relates most closely to the published 2022 methods.

We have compared our results to two versions ("experimental_sentinel1_snow_depth_data" and "West_US_Canada"), resampled our retrieved snow depths and lidar snow depth maps to the resolution of the C-SNOW products and compared all three products together, applying the stated parameters from Lievens et al (2022). We show here the results from the comparison with the "West_US_Canada" version because it had the highest correlation between our retrievals and the C-Snow datasets. We ran this comparison over all 9 lidar acquisitions and computed site-by-site correlations between the two retrievals and the lidar datasets. With so much uncertainty and our overall conclusion that much more complex algorithms are necessary anyways, we think it would be confusing to show too much of this algorithm intercomparison in the main publication or appendixes.

11. Figure 3 panel b: I guess x-axis label could be just "Snow depth" since both lidar and S1 SDs are presented.

    Changed to "Snow Depth"